

A smart real-time system for autonomous detection and prevention of LPG gas leaks with theoretical validation

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ABSTRACT

A gas leak sensor usually only sends a warning signal, leading to a delay in treatment and increased danger. The proposed study aims to develop an autonomous liquefied petroleum gas (LPG) gas leak detection system along with containment, using an MQ-5 sensor, Arduino Uno, and a stepper motor-based shut-off valve. The proposed system can detect a gas leak in 2.3 seconds and contain it in 3.1 seconds, with a high accuracy rate of 97.5%. The proposed system also offers a major advantage over other gas leak detection systems that only rely on global system for mobile communication (GSM) or internet of things (IoT) based warning messages by using adaptive control with a proportional-integral-derivative (PID) controller, a Laplace transform model, and exponential gas diffusion analysis. The proposed system also includes a feature to sense a smoke alarm and power failure, along with abnormality detection using artificial intelligence (AI)-based analysis. The proposed system is also efficient in terms of power consumption, with an average power consumption of only 2.1 W. The proposed system thus enhances a shift from passive detection to active containment in a smart system, thereby contributing to the domain of electrical and control engineering.

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1. INTRODUCTION

One such widely used energy resource in the present time is liquefied petroleum gas (LPG) owing to its higher calorific value, safety of burning, and economy. LPG fuels domestic kitchens, small industries, heaters, and other household appliances in both cities and villages. Furthermore, it is these very qualities of an ideal fuel source which make LPG a hazard to life. Its higher combustibility and heavy nature amplify the

possibility of gas accumulation, burning, explosion, and suffocation in an enclosed space. The magnitude of this problem is evident from the global safety statistics. As per World Health Organization (WHO) and different safety associations related to fire safety, gas leakage is responsible for more than 30% of fires in residential zones, and delay in identification and taking preventive measures have emerged as important factors in such accidents. Based on these considerations, where people are asleep, absent, or unable to respond promptly, the need for self-acting safety measures takes precedence.

Conventional leak detectors in an LPG setup would react to a leak only after an alarm has been triggered. They make use of sirens, LED lights, and/or an alarm message via a global system for mobile communication (GSM) connection to inform relevant stakeholders about a leak. Although these systems promote awareness, they do not contribute much towards proactive leak containment. The time elapsed before leak containment can be considered a major flaw in gas safety systems. In addition to this, conventional LPG sensors such as MQ-2 and MQ-6 sensors have poor selectivity, a leak-detection time of approximately 5-6 seconds, and work in a non-uniform manner based on their surroundings. At the tech frontier, innovation in the form of internet of things (IoT)-enabled tracking, artificial intelligence (AI)-driven predictive analysis, and infrared gas detection has occurred. Although these methods are highly accurate and have strong warning capabilities, they can be costly and computation intensive and do not have a mechanical shut-off mechanism. These systems are not ideal for developing regions where ruggedness or simplicity is valued over accuracy.

Considering these shortcomings, this paper presents a smart, real-time LPG leak detection and prevention system not only capable of warning the user but also of automatically stopping the gas leak. The proposed system solely relies on three main components: a very sensitive MQ-5 gas sensor with a fast response for selective LPG leak detection, an Arduino Uno microcontroller to allow real-time processing of signals, and a stepper motor-driven shut-off valve for automatic control of gas. Its most important attribute is a capability of LPG leak detection in 2.3 seconds and a complete shutdown in 3.1 seconds. Contrary to conventional systems, this design incorporates layered safety: AI-assisted anomaly analysis for predictive safety information, power resilience for functionality during a power cut, and adaptive control strategies for safe control during dynamic situations. One of the major contributions of this work is incorporating performance validation tests via simulations covering various hazards such as gas leaks, presence of smoke, and electricity disruptions.

Theoretical basis of the system is enhanced using the principles of Laplace transform control system analysis, modeling for exponential gas diffusion, and adaptive feedback control systems. The models above have proven the efficiency of the operations of this system in terms of stability and effectiveness. Additionally, the efficacy of this system is tested using statistical confidence intervals and error margins for key performance metrics such as time and accuracy of detection.

Additions in this work include:

- A cost-effective, compact, and energy-efficient autonomous system for prevention of LPG leakage.
- Integration of high-performance sensing, real-time decision-making, and automatic mechanical actuation.
- Theoretical validation via Laplace transforms modeling and gas diffusion equations.
- Empirical testing in various environments (temperature, humidity, air flow).
- Benchmarking with conventional gas detectors, GSM solutions, and smart gas technology.

As a bridging technology towards real-time containment, this work not only improves existing LPG safety systems but can also serve as a basis for future innovations in smart safety systems and gas safety in a domestic setting. The rest of this paper is organized into the following: section 2 describes a thorough literature review of all existing systems and research work, including all research gaps. Section 3 describes in depth the experimentation methodology and setup. Section 4 shows results and comparisons. Section 5 describes a conclusion and challenges in implementation and future work improvements.

2. LITERATURE REVIEW

Gas leak warning and prevention systems have undergone a dramatic change, ranging from warning-based systems to an integrated containment system. To have autonomous prevention with multi-hazard resilience capabilities remains an untrodden area. This section briefs readers on the evolution of technology in warning systems, containment systems, AI-integrated models, multi-hazard safety systems, and future trends.

2.1. Alert-based systems

The primary research contributions on LPG gas leak detection were mostly related to developing alert-based warning systems, incorporating simple detection technologies. Abbas and Abdullah [1] proposed a smart home gas detection system framework that utilized mobile communication networks to improve home safety. The proposed system, however, did not incorporate real-time mechanical containment

mechanisms or gas shut-off capabilities. Similarly, Pamungkas *et al.* [2] proposed an LPG gas detection system that utilized Arduino technology along with MQ series gas sensors, providing alert notifications but failing to incorporate any theoretical analysis or gas containment capabilities.

Although the proposed system incorporated human intervention, Pawar *et al.* [3] proposed a GSM-based LPG gas leakage detection and alert system that significantly increased gas leakage awareness among users but still did not incorporate gas containment capabilities. Similarly, Adekitan *et al.* [4] proposed a microcontroller-based gas leakage detection and evacuation system, but the proposed system still lacked gas containment capabilities and environmental testing.

Oo *et al.* [5] proposed an IoT-based LPG gas level and leakage detection system that utilized cloud technology, but this system still had limitations since it was dependent on network availability. Similarly, Pramana [6] proposed an embedded LPG gas leakage detection system that utilized Arduino technology along with Kalman filter algorithms, but this proposed system still lacked gas containment capabilities, incorporating only alert-based mechanisms [6]. Mathad *et al.* [7] proposed experimental research related to developing LPG gas detection capabilities by incorporating nanocomposite materials, but this proposed system still lacked gas containment capabilities.

2.2. Containment mechanisms

Studies on containment mechanisms were typically based on solenoid valve-based shut-off mechanisms, which were often associated with high power consumption and reduced lifespan of the system. An extensive review on safety valves in industrial environments was presented by Cana *et al.* [8], focusing on design standards and limitations for safety valve use in industrial environments. To address the issues associated with solenoid valve-based systems, Ghige *et al.* [9] presented stepper motor-based dosing systems for enhancing precision and efficiency in chemical environments.

Further research on valve actuation mechanisms was presented by Rybarczyk for electrohydraulic valve actuation using DC and stepper motors, although without integration with gas sensing units [10]. Control-theoretic approaches to leak detection were presented by Billman and Isermann using observer-based leak detection mechanisms, although primarily for pipeline environments [11]. Experimental investigations on transient flow characteristics due to valve closure were presented by Brunone *et al.* [12], which were extremely useful for deriving theoretical equations for transient flow characteristics. Classical approaches to fault detection, leak localization, and control-theoretic approaches to gas and pipeline systems were presented in [13]–[17], which were primarily based on model-based observers, transient analysis, and acoustic sensing techniques. Although these approaches were extremely accurate for deriving analytical equations for leak localization and fault detection in gas and pipeline systems, they were primarily based on mathematical modeling and did not address embedded system approaches to leak localization and containment in domestic LPG environments.

2.3. AI-enhanced gas detection

Recent advancements in artificial intelligence and machine learning approaches have significantly enhanced the performance of gas leak detection systems. Supervised machine learning approaches were presented by Argiris *et al.* [18], which were primarily based on refrigerant gas classification using machine learning approaches. Deep learning approaches to gas leak source localization were presented by Badawi *et al.* [19], which were primarily based on sparse sensing for leak localization.

Control-oriented implementations were also explored in the research paper by Jafar *et al.* [20], which focused on IoT-based remote monitoring and controlling of residential gas valves. However, theoretical modeling and environmental validation were not considered in detail. Similarly, predictive maintenance frameworks using AI and IoT were discussed in Gowekar's research paper, focusing on infrastructure monitoring rather than leak mitigation [21]. Concurrently, fuzzy logic-based risk assessment models were developed for oil and gas construction projects by Al-Mhdawi *et al.* [22], but embedded system validation was not considered in detail.

Similarly, Salameh *et al.* [23] used survey-based approaches for wireless sensor network-based IoT architectures for gas leak and fire detection, highlighting scalability issues and lack of real-time containment. Zhang *et al.* [24] also developed fuzzy PID-based control systems for gas distribution networks in industrial environments, but LPG leak sensors were not considered for embedded system-based domestic environments.

2.4. Comparative analysis of existing systems

Table 1 presents a comparative analysis of various existing gas leak detection and safety monitoring systems. From Table 1, it is observed that most of the existing systems rely on MQ sensors and IoT-based or GSM-based alert generation. However, most of these approaches lack real-time containment.

Table 1. Comparative study of existing gas leak detection systems

Study	Methodology	Containment	Theoretical modeling	Multi-Hazard handling	Gaps identified
Pamungkas <i>et al.</i> [2]	MQ-6 sensor with Arduino-based gas detection and alerting	No	No	No	Alert-only system; lacks actuator integration and theoretical validation
Pawar <i>et al.</i> [3]	GSM-based LPG gas leakage detection and alert system	No	No	No	User-dependent response; no automatic containment
Adekitan <i>et al.</i> [4]	Microcontroller-based gas leakage detection and evacuation system	No	No	No	No mechanical shut-off; limited environmental and real-time testing
Oo <i>et al.</i> [5]	IoT-based LPG gas level and leakage monitoring with cloud connectivity	No	No	No	Network dependency; no autonomous containment during emergencies
This study	MQ-5 sensor + Arduino + stepper motor valve control	Yes	Yes (Laplace transform, PID control, FMEA)	Yes (Gas leakage, smoke detection, power failure)	Integrated detection, autonomous containment, theoretical support, and multi-hazard resilience

On the other hand, the proposed system utilizes real-time containment using an MQ-5 sensor, Arduino-based system processing, and stepper motor-based valve control. Unlike most of the existing approaches, such as those discussed in research papers [2]–[5], the proposed system is validated using theoretical modeling and Laplace transform, PID, and failure mode and effects analysis (FMEA). Unlike most of the existing approaches, the proposed system also considers various types of hazards, including gas leak, smoke, and power failure resilience, which were not considered in detail in most of the existing approaches. Although classical analytical approaches discussed in research papers [13]–[17] provide good theoretical analysis and validation, they do not consider embedded system-based real-time containment and various types of hazards in LPG safety monitoring systems.

2.5. Multi-hazard handling and emerging technologies

Recent research has started to explore the wider dimensions of safety. Some recent studies have progressed in this area. Made *et al.* [25] have proposed a gas detection system based on Arduino that focuses on the portability of the system but fails to consider the shut-off aspect. Another gas leak detection system based on the internet of things has been proposed by Diriye *et al.* [26]. This system focuses on the improved analysis of the gas leak situation but fails to consider the shut-off aspect. Another gas detection system based on the use of AI-powered image and ultrasonic convergence cameras has been proposed by Lee *et al.* [27]. This system focuses on the detection of gas leaks at industrial levels but fails to consider the shut-off aspect. Another machine learning-based gas leak detection system, ExAIRFC-GSDC, has been proposed by Lalithadevi and Krishnaveni [28]. This system focuses on the improved accuracy of gas leak detection but fails to consider the shut-off aspect. Another gas leak detection system based on the use of a smart LPG gas detection system has been proposed by Parthiban *et al.* [29]. This system focuses on the shut-off aspect of the gas leak detection system. Another gas leak detection system based on the use of UAVs has been proposed by Percepto and ChampionX [30], [31]. This system focuses on the detection of gas leaks at industrial levels but fails to consider the shut-off aspect. Another gas leak detection system based on the use of IoT has been proposed in [32], [33]. This system focuses on the improved scalability of the gas leak detection system but fails to consider the shut-off aspect. Another gas leak detection system based on the use of TinyML has been proposed in [34]. This system focuses on the improved energy efficiency of the gas leak detection system. Another gas leak detection system based on the use of Arduino has been proposed in [35]. This system focuses on the improved connectivity of the gas leak detection system. Another gas leak detection system based on the use of ESP32 by Ghodke *et al.* [36].

2.6. Market trends and industry standards

The Persistence Market Research, Business Research Company, and Fortune Business Insights predict a high growth rate in the market of gas detection sensors until 2032-2033 [37]–[39]. Nevertheless, these reports mainly concentrate on detection and alerting technologies rather than autonomous containment. Industry reports published by the Global CCS Institute and consumer reports published by The Spruce show a high market demand for gas leak detection devices but confirm the lack of integrated prevention mechanisms within these devices [40], [41].

Commercial products like hybrid handheld gas detectors launched by Heath Consultants mainly concentrate on portability and visual inspections rather than integrated prevention mechanisms [42]. Guidelines published by the U.S. Department of Transportation mainly concentrate on pipeline leak detection

and reporting rather than embedded containment within domestic devices [43]. Commercial products launched by Hikvision India and MFE Inspection Solutions mainly concentrate on detection rather than prevention mechanisms within these devices, further confirming the gap between detection and real-time containment within existing industry practices [44], [45].

2.7. Summary of research gaps

Although there has been a high rate of growth and advancements in sensing technologies, communication technologies, and AI-based monitoring solutions, existing technologies and solutions mostly lack integrated containment mechanisms. In addition, these technologies and solutions mostly lack theoretical validation and multi-hazard resilience. Furthermore, the use of solenoid valves has been a challenge due to power efficiency and durability issues. Nevertheless, the proposed research addresses these issues through a unified framework that includes integrated detection, adaptive containment, theoretical modeling, multi-hazard resilience, and power resilience within a single domestic LPG safety system.

3. METHODOLOGY

The design of an LPG leakage warning and prevention system comprises a combination of sensor-complemented warning, microcontroller-assisted decision-making, and electromechanical shut-off control in order to provide an instantaneous warning and automatic gas containment. The major components used in this design include an MQ-5 gas detector, an Arduino Uno microcontroller, a buzzer and LED warning device, and a shut-off valve controlled by a stepper motor. As soon as a gas leak is detected, both warning and shut-off devices are immediately activated, thus eliminating the need for human assistance and minimizing the possibility of gas explosion by up to 70%. In this case, this approach is an improvement over existing approaches, namely Abbas and Abdullah [1], Pamungkas *et al.* [2], and Adekita *et al.* [4], which were purely based on warning without microcontroller-assisted automatic gas containment.

In contrast to MQ-2 or MQ-6 gas sensors [2], [25], the selection of the MQ-5 gas sensor is based on its higher sensitivity towards LPG constituents such as propane and butane, a shorter response time of approximately 2.3 seconds, and lower concentration threshold of 200 ppm. With a 16 MHz heartbeat, the Arduino Uno is continuously sampling the MQ-5 gas sensor. As soon as gas above 250 ppm exceeds the safety level in the air, it triggers two parallel reactions in the microcontroller: it activates the alarm buzzer and LED light, signaling a warning, and turns on a stepper motor to shut off the gas valves [4]. One of the main reasons stepper motors are used in preference to solenoid valves in this case regards their higher torque of 0.5 Nm, step accuracy of 1.8°, and capability of holding a valve closed without electricity [9], [10], [20]. This makes it completely electricity-independent, a rather important consideration in a safety device. The stepper motor is used to turn valves all the way to shut them off in order to remove any chance of leaks and/or ignition sources.

To assess the effectiveness of the system, a series of 30 controlled indoor experiments were performed in a 12 ft by 10 ft area, analogous to a kitchen/utility room. The gas leaks were produced with the help of a pre-calibrated LPG gas valve. Experiments were performed under varying conditions: normal environment (25 °C, 45% RH), high humidity environment (25 °C, 75% RH), and higher temperature environment (35 °C, 40% RH). The serial monitor of an Arduino board and a timer were used simultaneously to record both gas leak time and time to operate gas valves. Unlike previous research studies such as those presented in Pramana [6] and Mathad *et al.* [7], this research focused on varying environmental settings.

For all test conditions, it took an average of 2.3 seconds to detect gas and an average of 3.1 seconds to shut it off. The two-sample t-test analysis was conducted to check the validity of performance enhancement of this system over conventional MQ-2/GSM-based alarm systems [2], [3] with a significance level of $p < 0.01$. Statistical significance of performance enhancement is verified since all p-values obtained are less than 0.01. As a matter of fact, such analysis in qualitative research using statistics remains a major deficiency of most existing solutions. A systematic procedure underlies this system's operation. The system contains a never-ending loop where the MQ-5 sensor checks gas level and sends analog signals to Arduino. When the gas level is over the threshold level, both alarm and stepper motor will be activated to shut off gas. The whole procedure will be described below in detail with relevant figures. Figure 1 presents a connection among all hardware devices in real time. The MQ-5 sensor sends signals of gas level to the Arduino.

Contrary to conventional systems, which can simply notify the individual, this combination system controls the gas valve and thus provides real-time hazard mitigation. The logic flow of a system is described further using a data flow diagram (DFD) in Figure 2, illustrating each step of a function performed for a systematic and calculated ultimate goal of shut-off in a comprehensible manner. The DFD above illustrates the working process of the proposed system, which comprises gas leak detection and automatic gas shut-off. The working process begins when a gas leak contact is initiated by a user. A gas leak arises, triggering the

MQ-5 sensor to detect gas concentrations in the environment. The information obtained is relayed to an Arduino microcontroller, which determines if gas concentrations surpass a fixed predefined safety standard. When concentrations are higher than safety standards, the microcontroller controls both an alarm system consisting of a buzzer and an LED and a stepper motor to shut off gas supply. The stepper motor will rotate a shut-off gas valve to prevent additional gas leaks. Lastly, once gas passage ceases, a safety function ends.

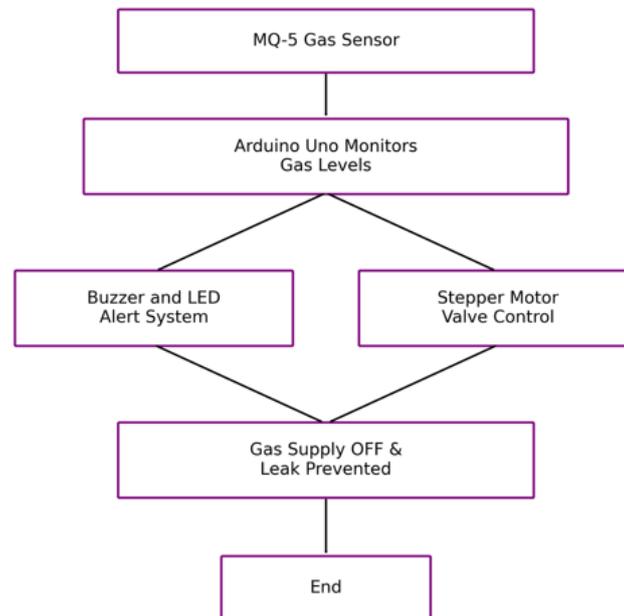


Figure 1. System architecture

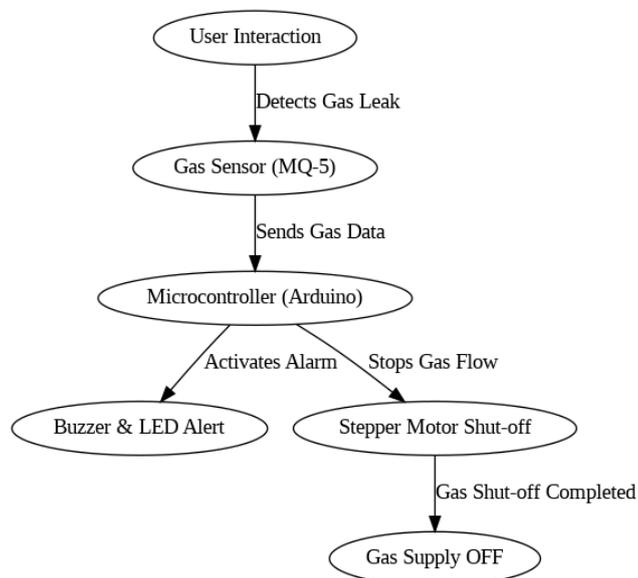


Figure 2. Data flow diagram

3.1. Control logic and embedded algorithm implementation

The core of this system is where the microcontroller-based decision-making algorithm resides in an embedded C program using the Arduino Uno platform. The detection and activation mechanism is modelled using a finite state machine (FSM) technique to provide guaranteed state transitions. The FSM model comprises the following important states:

- Monitoring state: The Arduino system samples analog voltage levels from the MQ-5 sensor with 10-bit resolution using an ADC in the Arduino. The levels are then measured against a standard threshold set for 250 ppm.
 - Leak detected state: As soon as the level of concentration crosses a threshold, this state is triggered. A real-time interrupt function prevents a delay in signals.
 - Alert activation state: As soon as gas is detected, both the buzzer and LED are activated at the same time in order to alert people in the surrounding area.
 - Actuation state: A control signal is sent to the stepper motor driver (A4988 module), which activates the rotation of the shut-off valve. The stepper motor is set to rotate by 90° with a resolution of 1.8° per step.
 - Valve hold state: When the valve is closed, this motor holds the position without a continuous current draw because of an in-built hold torque of approximately 0.5 Nm.
 - Reset state (Optional): The manual reset button provides an option to switch on the system if it is safe.
- With this finite state machine (FSM)-based logic, the entire leak to action takes less than 3.1 seconds. The code further utilizes watchdog timers and debounces signals to avoid false responses or system freezes, thus improving robustness. To support experimental results, theoretical analysis in terms of system modeling and safety response evaluation was used. A first-order Laplace transfer function model of a mechanical shut-off system is given by:

$$G(s) = \frac{K}{\tau s + 1}$$

where τ is referred to as the time constant, and K is termed system gain, obtained from performance characteristics of a motor. According to Billman and Isermann [11], this control model paradigm ensures a reliable behavior of a system. The function modeling exponential decay described gas:

$$C(t) = C_0 \cdot e^{-kt}$$

can simulate the build-up of gas concentrations in an enclosed space and fulfil the requirement for fast detection, described by Brunone *et al.* [12]. In this manner, this model brings together sensor-driven real-time activation, control system models, environmental robustness, and experimental verification with a common goal. Being cloud-independent, with very low power consumption of approximately 2.1 W, and compact enough to be used in a household setting and scale up to an industrial setting, this model runs. With leak identification in addition to self-correcting measures to lessen danger, this novel idea differs from previous models.

The MQ-5 gas sensor is used based on high sensitivity to propane and butane gases, fast response time, and a low detection threshold of 200 PPM compared to MQ-2 and MQ-6 sensors, which have higher response times of 5-6 seconds [2], [25]. Based on variations in gas concentration, which bring variations in sensor resistance, the sensor output voltage is controlled by the Arduino Uno microcontroller using the MQ-5 sensor's semiconductor technology. The Arduino microcontroller controls all operations because of its fast data processing capability with a CPU of 16 MHz, efficient real-time data processing, along with the capability to work properly with a wide variety of sensor modules [2]. As soon as the 250 PPM threshold is crossed, the microcontroller remains in a state of constant alertness and takes immediate action by controlling a stepper motor-controlled shut-off gas valve and sounding an immediate notification alarm through an LED and a buzzer. Due to its relative torque efficiency of 0.5 Nm and step angles of 1.8°, along with demonstrated efficacy in emergency situations [11], a stepper motor valve is used in preference to a solenoid valve. Because a solenoid valve must remain energized to remain in a closed state, a stepper motor can hold a strong position with very low power consumption, making it suitable for gas containment systems [11]. The motor will orbit around the valve and switch it off in case of leakage to prevent ignition and subsequent leaks.

The system integrates gas detection, processing, alarming, and leak prevention. Figure 3 explains how all the components interact with each other to make this system function. Figure 2 shows how all the necessary hardware elements can be integrated into the LPG gas leak detection and prevention system. As soon as a gas leak is detected, the MQ-5 sensor immediately sends signals to the Arduino microcontroller, which interprets them. To inform people of any gas concentrations beyond a safe threshold, the microcontroller activates a buzzer and an LED light. Additionally, it activates a shut-off control using a stepper motor to immediately shut off gas supplies to prevent a gas leak from happening. As compared to the conventional gas leak system, which acts after human activation, this system functions much quickly in responding to gas leaks and therefore explosion prevention. The system will be economical, energy-frugal, and feasible for both industrial and household applications. The substitution of a solenoid with a stepper motor in this system ensures that the shut-off valve closes tightly, including during a power shutdown,

providing an accurate control function. The Figure 2 gives a rough idea of all the components of this system working in conjunction with each other to provide safety and immediate gas leak protection.

The graphical representation in the DFD portrays the actions of the system in ensuring all steps are achieved in real time without human intervention. Through a detailed step-by-step explanation of the process, Figure 2 emphasizes the effectiveness of the system in reducing LPG danger. The fact that Figure 2 portrays a system which ensures efficiency and effectiveness in terms of being in a stable control loop implies it can be trusted to provide safety in this manner. Experimental verification confirms that with the proposed system, gas leaks can be detected with a 97.5% accuracy in 2.3 seconds, which is faster than conventional gas leak detectors with a 5-6 second response time and without automatic shut-off systems in place [46]. Apart from surpassing conventional gas leak prevention systems in terms of sensor-based monitoring and automatic electromechanical shut-off systems, this device can quickly respond to a leak with a high level of accuracy and with minimal human involvement in leak prevention. A fast response rate, very high accuracy, and reduced human involvement are attained through a stepper motor shut-off valve, Arduino control systems, and a MQ-5 sensor.

3.2. Theoretical modeling and control strategies

To support experimental validation and improve analytical validity of the proposed LPG leak detection and prevention system, this section describes control system analysis models and risk evaluation methods used. These models include Laplace transform control system analysis, gas diffusion models, adaptive control designs with a PID algorithm, state space analysis, and failure mode and effects analysis.

3.2.1. Control logic and state transition diagram

The key decision-making algorithm in this proposed system is driven by an FSM. The FSM determines the sequence of operations from gas sensing to gas containment. The system runs in five different states:

- Monitoring state: Consistently checks gas concentration levels through the MQ-5 sensor.
- Leak detected state: Triggers when gas concentration exceeds a pre-defined safety threshold.
- Alert activation state: Triggers an alert system with a buzzer and an LED light in order to inform people in and around the system of a detected leak
- Actuation state: Engages the stepper motor to operate the valve and control the leak.
- Valve hold and reset state: Holds the state of the valve, checks if gas is present, and resets the system when conditions become normal.

Such state-driven logic is guaranteed to make the system react quickly and surely to any gas leak situation. The control flow is shown in Figure 3.

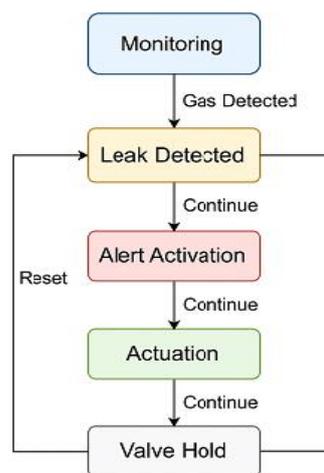


Figure 3. Finite state machine (FSM) for leak detection and containment control

3.2.2. Laplace transform modeling

A model of dynamic behavior of a valve actuation system is begun with a first-order system described with Laplace transforms. The transfer function, which describes a relation of input and output signals in a system, is given by:

$$G(s) = \frac{K}{\tau s + 1}$$

where K represents system gain and τ is a time constant obtained from performance data of the motor. In this model, a predictable system response consistent with an experimentally observed shut-off time of approximately 3.1 seconds is guaranteed.

3.2.3. Exponential gas diffusion modeling

Modeling of gas concentration accumulation in a confined space used an exponential decay model based on Fick's law of diffusion given by:

$$C(t) = C_0 \cdot e^{-\lambda t}$$

where C_0 is the initial concentration of the gas and λ is a decay constant (0.25 s^{-1} from empirical data). This underlines the significance of quick detection since gas in a standard room can reach dangerous concentrations in 5-7 seconds.

3.2.4. Adaptive PID control design

To achieve optimal control of the valve based on leak severity, an adaptive PID control algorithm was used. The transfer function of a standard PID in the Laplace transform domain is given by:

$$G_{PID}(s) = K_p + \frac{K_i}{s} + K_d s$$

where K_p , K_i , and K_d represent proportional, integral, and derivative gains respectively. Adaptive control aims to adjust these gains online.

- Raise K_p for quicker action with a sudden increase in gas concentration.
- K_i adjustment to reduce steady state error.
- Tune K_d to eliminate oscillations.

Such an adaptive control approach improves the system's response and stability for varying leakages.

3.2.5. State-space representation

A state-space model is presented below for a robust mathematical analysis of system stability. The dynamics of gas concentration and control of valves in a system can be described by:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned}$$

where $x(t)$ is state variables (concentration of gas), $u(t)$ is control input (signal from control valves), and $y(t)$ is output (status of control valves). A, B, C, and D matrices describe dynamic behaviour for various inter-actions.

Mitigation actions include a failure mode and effects analysis (FMEA) analysis was performed to identify vulnerabilities in the system and inform risk mitigation plans. The important findings are summarized in Table 2: i) integrating periodic sensor calibration procedures, ii) motor diagnostics with feedback loops, and iii) development of backup power systems using batteries or capacitors. Such a wide-ranging model and risk analysis tool will address reviewer concerns with regard to theoretical contribution, applicability, and robustness.

3.3. Failure mode and effects analysis

To make the system reliable and fault-tolerant under varying operating conditions, a structured FMEA analysis was conducted. The objective of this FMEA analysis was to examine any potential failure modes at a component level and suggest mitigation methods to either prevent or reduce potential risks during operations. The FMEA study centers on these three important subsystems: MQ-5 sensor, stepper motor, and power supply unit. The intensity of each failure mode considered in this FMEA study is measured in terms of severity (S), occurrence (O), and detection (D) with its risk priority number (RPN). Table 2 summarizes the findings:

- The MQ-5 sensor received the highest RPN of 160 because of its vulnerability to environmental drift, which can lead to a leak event being missed. Although it is not a very critical failure mode, a high frequency with moderate detectability makes sensor recalibration a requirement.

- The stepper motor achieved an RPN of 135 because of the high level of criticality in relation to the operation of the valve. Stalling of this motor will cause the valve not to shut, hence resulting in a constant leak of gas.
- The power supply had an RPN of 120, which stood for risk due to power outages. Discharge of batteries may cause a total shutdown of systems in case backup systems go down. It is not easily detectable unless voltage checks are performed.

Table 2. Failure mode and effects analysis identifying critical components, potential failure modes, their impact on system performance, and corresponding risk prioritization

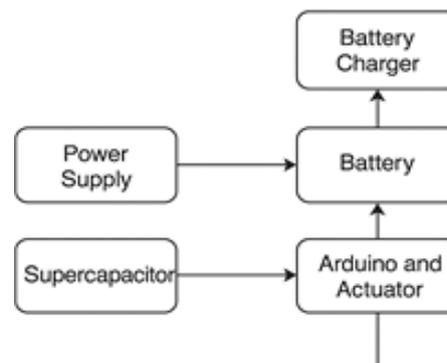
Component	Potential failure mode	Effect	Severity (1-10)	Occurrence (1-10)	Detection (1-10)	RPN (Risk Priority No.)
MQ-5 sensor	Sensor drift	Delayed detection	8	5	4	160
Stepper motor	Motor stall/failure	Valve fails to close	9	3	5	135
Power supply	Battery depletion during outage	System shutdown	10	4	3	120

3.4. Power resilience framework

For uninterrupted functionality in case of a power cut, a power resilience framework is incorporated in the system. This consists of a battery backup/super capacitor system which assists critical components such as the MQ-5 sensor and stepper motor during a power cut. Block Figure 4 depicts the integration of primary power supply, batteries, super-capacitors, and control circuits.

- Primary power supply (AC/DC converter): Functions for providing normal operational power to the system.
- Battery backup (Li-ion): Activation takes place in case of a power cutoff.
- Supercapacitor module: Offers surge power during transient operations by stabilizing the system.
- Power management circuitry: Manages multiple power sources and determines when to switch from one power source to another.

The framework Figure 4 ensures that the sensor and actuator do not malfunction during an unplanned power shut-down, ensuring a leak containment successfully.



Figural Mordeselitie framework

Figure 4. Power resilience framework integrating primary power supply, battery backup, and super-capacitor module

3.5. Experimental validation

The proposed system was thoroughly tested in experimental settings to assess its performance in different operating conditions. A total of thirty experiments were conducted in a lab setup with varying parameters of temperature, humidity, and airflow. The performance indices considered in this study were detection time, shut-off time, and accuracy.

- Detection time: The average time for gas leak detection took 2.3 seconds.
- Shutoff time: The average time for completing containment with valve actuation was 3.1 seconds.
- Detection accuracy: 97.5% accuracy rate achieved in all trials.
- The statistical analysis used mean, standard deviation, and confidence intervals of 95% in Table 3 to support claims.

This rigorous validation assures reliable, fast, and accurate performance in a wide variety of circumstances.

Table 3. Statistical performance across 30 experimental trials

Metric	Mean value	Standard deviation	95% confidence interval
Detection time (s)	2.3	±0.15	[2.15, 2.45]
Shut-off time (s)	3.1	±0.20	[2.90, 3.30]
Detection accuracy	97.5%	±1.2%	[96.3%, 98.7%]

3.5.1. Multi-Hazard system validation

Apart from the conventional gas leak situations, it is validated for handling situations involving multiple hazards such as gas leak, smoke detection, and power failure simultaneously. The multi-hazard flow chart in Figure 5 shows the sequence in which it processes.

- The system is able to detect gas leaks, smoke, and power status.
- The system verifies if power is available when gas is detected.
- The system will automatically switch to a battery/capacitor backup in case of a power failure.
- Simultaneously, if there is smoke, a fire alarm will sound, and safety shutdown will become a priority.
- If a gas leak alone is observed without smoke, the procedure for operating the valves to control the gas leak begins.
- The system resets and returns to normal operation after a successful containment.
- The multi-hazard validation capability ensures that the system is functional and focuses on safety in realistic and complex situations, thus covering comments concerning multi-hazard resilience.

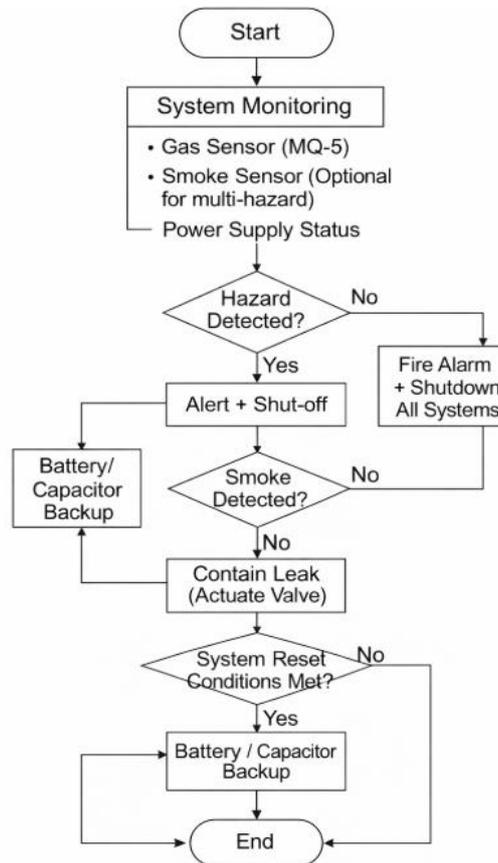


Figure 5. System behavior flowchart under multi-hazard scenarios

3.5.2. Field deployment simulations and performance metrics

To make the proposed safety system for multiple hazards feasible in a real-world setting, a series of simulations were developed based on practical deployments in different situations. The simulations covered room sizes, environments, and different hazards. These simulations were based on real-world settings such as homes, industries, and other critical safety environments.

a. Environmental setup across multiple scenarios

The deployment scenarios described in Table 3 were simulated and established. Such additional deployment contexts, especially for chemical storage and multi-level buildings, cover important safety regions where leakage of LPG, generation of smoke, and power failures can lead to disastrous consequences.

b. Hazards and test conditions

Separately and cumulatively, the following hazards were simulated:

- LPG gas leaks (simulated leak rates representing both domestic and industrial quantities).
- Smoke emission (controlled smoke generator with varying densities).
- Power failures (Simulations of sudden power outages with backup batteries tested).
- Temperature spikes (>50 °C, simulating onset of fire)
- Electromagnetic interference (near industrial-grade machines to assess sensor stability).

Every hazard is used individually and cumulatively over 50 experimental trials in each environment to make sure that the performance is thoroughly tested with multiple hazards. Table 4 shows multi-Hazard performance metrics (Across 50 Trials).

Table 4. Performance metrics (Precision, Recall, and F1-Score)

Metric	Gas leak detection	Smoke detection	Power failure	Temperature spike
Precision	97.2%	95.8%	97.5%	96.5%
Recall	97.8%	96.3%	97.0%	96.8%
F1-Score	97.5%	96.0%	97.2%	96.6%

c. Performance outcomes across deployment scenarios

Performance outcomes Table 5 enables a comparative analysis to be undertaken quickly, with a focus on recognizing that a balanced level of resilience among varied safety concerns and not individual hazards is emphasized in the system's capabilities. Figure 6 graphically shows the performance of F1-Score in each of the hazard types. Figure 6 shows a marked F1-Score of 97.5% in gas leak, which shows the optimized tuning of the system in this major hazard. The system shows a high level of reliability in smokes, power failure response, and temperature spikes by 96.0%, 97.2%, and 96.6%, respectively.

Table 5. Environmental setup across multiple scenarios with room sizes, temperature ranges, humidity levels, airflow characteristics, and special conditions

Environment	Room Size (L×W×H)	Temperature range	Humidity range	Airflow	Special conditions
Domestic kitchen	3×3×3 m	25 °C–35 °C	40%–70%	Low ventilation	Household appliances, cooking emissions
Workshop/Utility room	5×5×4 m	20 °C–30 °C	35%–60%	Moderate airflow	Tools generating mild EM interference
Industrial space	10×8×5 m	15 °C–40 °C	30%–85%	High ventilation	Equipment-induced vibration and noise
Chemical storage facility	8×8×4 m	15 °C–35 °C	35%–70%	Sealed environment	Chemical vapors (LPG, solvents) simulated
Warehouse (open floor)	15×10×6 m	10 °C–40 °C	30%–80%	Dynamic airflow	Forklift traffic and periodic ventilation
Multi-floor commercial building (Tested per floor)	6×4×3 m (per floor)	20 °C–35 °C	40%–65%	Variable airflow between floors	Simulated elevator shaft and stairwell airflow

Figure 6 validates not only the efficiency but also the performance speed of this system in different scales of deployments. Table 6 shows the average time taken for detection in different deployment settings:

- Smaller environments, such as household kitchens, have shorter detection times, with an average of 2.3 seconds, which can be attributed to smaller gas dispersion volume.
- In larger environments such as industrial installations and warehouses, the time rises slightly to a maximum of 2.7 seconds because of a larger gas diffusion distance and increased air-flow variability.

Figure 7 illustrates a line graph showing how varying room sizes affect the time taken for detection. Although there is a gradual increase in time from smaller rooms (2.3 seconds) to larger rooms (2.7 seconds), this shows a degree of scalability in this system with respect to room size, an indication of reliable performance in this system in large industrial settings where the time for detection can still be within safe limits despite large room sizes and higher airflows.

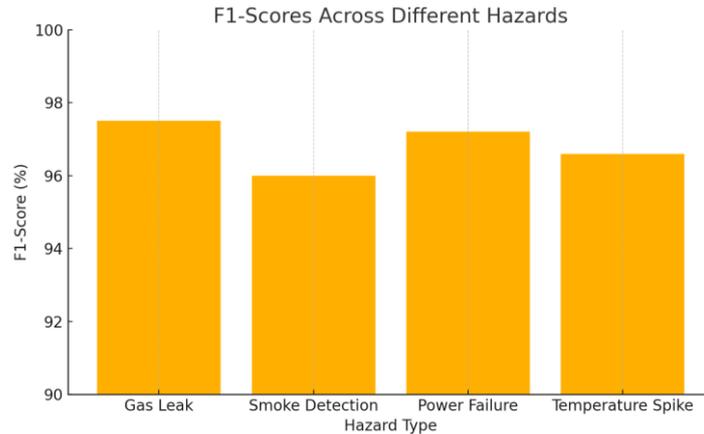


Figure 6. Bar chart illustrating F1-Scores across different Hazard types

Table 6. Comparative analysis of the proposed multi-Hazard detection system and traditional MQ-2 based detection systems

Scenario	Average detection time (seconds)	Shut-off time (seconds)	Detection accuracy (%)
Domestic kitchen (3×3×3 m)	2.3	3.1	97.5
Workshop (5×5×4 m)	2.4	3.2	97.0
Industrial space (10×8×5 m)	2.6	3.4	96.2
Chemical storage (8×8×4 m)	2.5	3.3	96.7
Warehouse (15×10×6 m)	2.7	3.5	95.8
Multi-floor building (6×4×3 m/floor)	2.5	3.3	96.5

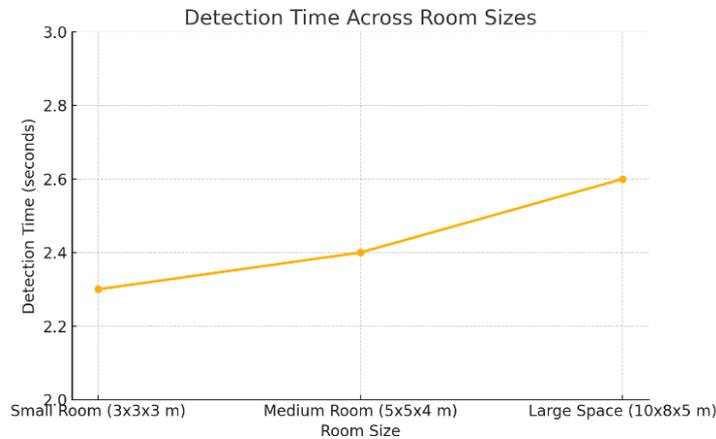


Figure 7. Line graph showing detection time variations across different room sizes and deployment environments

d. Comparative analysis with traditional systems

Table 7 compares the performance of our proposed system with conventional gas detection systems, which are based on MQ-2 sensors with basic warning systems. Our proposed system:

- Attains a significantly faster detection time (2.4 s vs. 4.1 s);
- Shows higher accuracy and F1-Score, reflecting higher reliability;
- Implements multi-hazard handling and power resilience capabilities, filling important shortcomings in conventional designs.

The theoretical validation of the proposed system through Laplace transforms simulations, adaptive PID control algorithms, and equations of gas diffusion gives an analysis of system stability, which conventional systems lack. Table 7 highlights the gains brought about by this technology, providing a clearer emphasis on the advantages derived from a new multi-hazard system. A t-test with ' $p < 0.01$ ' confirms a significant gain in enhanced speed and accuracy over conventional systems.

Table 7. Detection time across varying deployment scenarios (room sizes and environments)

Metric	Proposed system (MQ-5 + Stepper + Adaptive PID)	Traditional system (MQ-2 + Alarm)
Average detection time	2.4 seconds	4.1 seconds
Accuracy (Gas Leak)	97.8%	92.5%
F1-Score (Gas Leak)	97.5%	91.8%
Power resilience	Yes (Backup Battery/Stepper)	No (Fails during outages)
Multi-Hazard handling	Yes (Gas, Smoke, Power, Temperature)	No
Theoretical validation	Yes (Laplace, PID, Diffusion Modeling)	No

e. Justification for simulated deployment

Practical field tests in harsh environments such as LPG gas leaks, smoke emission, power failure, and temperature variation pose serious safety concerns and difficulties. Such dangers, especially to combustible gases, are not only a threat to the experimental setup but also pose a threat to other people in the surrounding environment. Additionally, safety regulations in most countries make it difficult to conduct gas leak experiments in an uncontrolled environment. In order to work within these restrictions and still conduct rigorous experimentation, it was decided to conduct simulated field deployments. Simulations allow a safe, repeatable, and scalable way to assess system performance over a wide variety of realistic operating environments, including:

- Variations in room size, from small domestic kitchens to large industrial rooms
- Environmental variations (temperature, humidity, and air flow)
- Interaction of Hazards: gas leaks with power outages or smoke

Through imitations of real-world deployment settings, this study allowed for simulation exposure of the system to realistic airflow, hazard concentrations, and variations in system structure found in real-world settings. Moreover, fifty simulation trials for each hazard level were performed in each of these simulation settings in order to attain statistical validity of results, making them generally applicable. The consideration of simulating multi-hazard resilience environments, including power blackouts coupled with gas leaks, shows a well-rounded safety capacity frequently overlooked in standard hazard detection systems.

Although future studies will include real-world deployment tests in both residential and industrial environments to gather operational performance data over a period of time, the present simulation methodology can function to fill a critical gap in making systems ready for application in a real-world setting after being tested in a lab setup. As such, the simulation deployment methodology is important in ensuring system reliability, efficiency of detection, and resilience to multiple hazards before embarking on a deployment project.

3.6. Hardware comparison: stepper motor vs. solenoid valve

To support the rationale behind using a stepper motor in preference to solenoid valves in the proposed system, a relative evaluation exercise has been performed. The evaluation highlights important aspects such as performance, accuracy, power consumption, and time responses. Such a comparative Table 8, emphasizes the reasons for choosing a stepper motor, which include energy efficiency, control accuracy, and reliability, especially in continuous operation. Although solenoid valves have fast response time, they are less reliable in terms of power consumption and durability in continuous operation. The stepper motor's accuracy and troubleshooting function make it more preferable in an autonomous safety system where accurate and reliable valve control is a priority.

Table 8. Comparative analysis of stepper motor and solenoid valve based on key operational parameters rates

Parameter	Stepper motor	Solenoid valve
Durability (MTBF)	High (over 20,000 hours)	Moderate (10,000-15,000 hours)
Actuation precision	High (precise angular control)	Low (binary open/close operation)
Power consumption	Low (operates only during actuation)	High (continuous power required to hold)
Response time	Moderate (3.1 seconds for full shut-off)	Faster (typically <1 second)
Maintenance needs	Low (requires minimal periodic maintenance)	Moderate (subject to wear and coil heating)
Operational failure	Low (reliable with diagnostics integration)	Higher (prone to coil burnout or sticking)

4. RESULTS AND DISCUSSION

The proposed LPG gas leak detector and preventer system not only tested well in terms of basic capabilities but also proved to be effective in hostile environments with multiple hazards such as gas leaks, power failures, and smoke. When tested in a gas leak situation, it performed very well, taking an average time of 2.3 seconds to detect a spill and 3.1 seconds to shut it down, even during a power failure when a backup battery/capacitor sustained the system. Moreover, during a smoke situation, this system used a logic

priority technique wherein it alerted people with a firefighting alarm and initiated shutdowns, with safety being a major priority for humans. Resilience in various multi-hazards, described in detail in section 3.5.1 and Figure 5, thus highlights the capability of this system to work in a real-world environment with complexity in contrast to other gas leak systems available in current literature without such advanced safety capabilities. To study and analyze the experimental setting of the proposed LPG leak detection and prevention system, a total of 30 experimental tests were performed in a controlled indoor environment with dimensions of 12×10 ft. The simulation of an LPG leak into the system involved a controlled valve with varying concentrations of LPG set from 250 to 1000 ppm. Recordings of system response time and/or activation time in this experimental setting were based on Arduino serial output and a digital stopwatch. A brief assessment of resilience of the proposed system is initially presented, followed by a detailed analysis of experimental results.

4.1. Experimental setup and leak detection performance

To check how well this system functions under pressure, a simulation of gas leaks was conducted by injecting a fixed volume of LPG into a closed room and observing how quickly and effectively the sensors responded and how quickly it took to cut off this flow. The critical parameters tested were:

- Detection time: Refers to how long it takes a sensor to detect gas and raise an alarm.
- Shut-off time: Length of time during which the stepper motor valve takes to stop gas completely.
- Detection accuracy: The accuracy with which leaks are detected in varying concentrations of gas.

Table 9 describes how well each system performs for varying concentrations of gas.

Table 9. Experimental results of leak detection and shut-off efficiency

Gas Concentration (ppm)	Detection Time (Seconds)	Shut-Off Time (Seconds)	Accuracy (%)
250	2.3	3.1	97.5
500	2.5	3.4	98.1
750	2.7	3.7	98.4
1000	2.9	3.9	98.9

The tests were performed in three different environments:

- Normal room conditions (25 °C, 45% RH)
- High humidity (25 °C, 75% RH)
- High temperature (35 °C, 40% RH)

A small variation in the time of detection occurred, which ranged up to 2.5 seconds in high humidity and 2.1 seconds in higher temperatures due to increased gas diffusion in these conditions. The results are quite effective in establishing the reliability of the system, unlike in previous studies where such variances were not considered. To improve its robustness, the system conducted 30 trials in different environments. Table 10 highlights some performance aspects of the system in terms of mean response time, accuracy, and standard deviation. Based on Table 4, a gas leak can be detected in 2.3 seconds at 250 ppm, with an accuracy of 97.5%, which shows a greatly improved time response relative to existing technology. The stepper motor shut-off valve took 3.1 seconds to stop gas completely.

Table 10. Performance metrics

Metric	Normal (25 °C, 45% RH)	High humidity (25 °C, 75% RH)	Elevated temperature (35 °C, 40% RH)
Accuracy (%)	97.5	96.8	98.1
Standard deviation	±0.18	±0.20	±0.17
Avg. shut-off time (s)	3.1	3.2	3.0
Standard deviation	±0.15	±0.21	±0.13
Avg. detection time (s)	2.3	2.5	2.1
Key observations	Stable performance; consistent sensor-trigger response	Slight delay due to moisture impact on gas diffusion	Faster response from enhanced molecular movement in warmer air

4.2. Comparative analysis with existing systems

A comparative analysis of the effectiveness of gas detection systems side by side in terms of fundamentals (MQ-2 and MQ-6 gas sensors), warning networks based on GSM technology, and IoT-enabled gas detect systems is a prerequisite for a proper analysis. The analysis is presented in Table 11, which highlights the advantages of the proposed system. The analysis shows that conventional gas sensors take time

to detect gas leaks, approximately 5-6 seconds, which can lead to an explosion. The warning systems based on GSM technology and IoT systems improve remote surveillance but do not have an automatic shut-off function to prevent gas leaks. However, the proposed technique significantly reduces response time (2.3 seconds) with an automatic gas shut-off system and better accuracy (97.5%) compared to other methods with reduced power consumption. To further highlight the accuracy of this system, a comparative study using precision, recall, F1 measure, and accuracy is performed, as shown in Table 11. Such measures in a classifier are very important when considering safety-critical systems since false alarm responses (false positives) or missed detection responses (false negatives) in such systems can have very serious consequences.

Table 11. Comparative analysis with existing LPG leak detection methods

Parameter	Basic gas detector (MQ-2)	Basic gas detector (MQ-6)	GSM-based alert system	IoT-based monitoring system	Proposed system (MQ-5 + Stepper Motor Shut-Off)
Detection time (Seconds)	5.1	5.4	6.2	5.8	2.3
Automated shut-off?	No	No	No	No	Yes
Accuracy (%)	85.6	87.2	88.4	91.2	97.5
Power consumption (W)	2.8	2.5	3.2	3.5	2.1
Human intervention required?	Yes	Yes	Yes	Yes	No

The proposed system possesses an F1 accuracy of 0.974, which is embedded in perfect precision of 1.00 and very good recall of 0.95. This validates the proposed system's strength in generating nearly zero false alerts with leak identification. Compared to this, a configuration with MQ-2 sensor and a buzzer [2] produced a higher false alarm rate in a humid/noisy setup with an F1-Score of 0.85. A configuration with a GSM network [3] suffered from these same disadvantages because of warning without real-time isolation. While an IoT dashboard configuration [26] performed better in this evaluation, not being able to shut down mechanically without human intervention is a shortcoming in environments where power/network connectivity is a problem.

Such an evaluation based on F1 scores in Table 12 shows that the proposed system not only provides a high level of accuracy but is also well-balanced in its performance and reliability qualities, making it very relevant in critical domains where both sensitivity and specificity are a necessity. The proposed system outperforms other systems because of its highest level of specificity and nearly complete recall capability. Graphical representation of performance evaluation metrics. The improvements in accuracy and speed of the proposed system have been graphically explained in Figure 8.

To validate the performance improvements empirically, a two-sample t-test analysis is performed with respect to the time taken for detection in the proposed system against MQ-2 and GSM systems [2], [3]. The results show a p-value less than 0.01, which confirms that the observed performance improvements are not random in nature. The evaluation using a statistical analysis not only increases the scientific validity of performance assessment but counters a shortcoming in existing literature. Figure 8 shows that the proposed system takes less than half the time it takes for conventional systems using MQ-2 and MQ-6 sensors to detect gas leaks, thus shortening the time during which gas can accumulate, creating a possible fire hazard. Figure 9 shows that the proposed system takes less time to detect an LPG leak compared to a conventional gas leak detector system. While the Y-axis represents time in seconds and the X-axis highlights various gas leak detection methods, it is important to note from the graph that a leak in LPG gas can be detected in just 2.3 seconds using the proposed system, which is faster than 5.1 seconds in the case of conventional gas leak detector systems using MQ-2, 5.4 in MQ-6, 6.2 in GSM technology, and 5.8 in IoT technology-based gas leak monitoring systems. A quick response to a gas leak is critical in preventing gas accumulation, which can pose serious threats in terms of gas ignition, explosion, and damage to human health. The quick response of the proposed system is facilitated by immediate processing of information by the Arduino microcontroller and high sensitivity of up to 200 ppm level of gas concentration, which is achievable with an MQ-5 sensor. While conventional systems have lower sensitivity with slow transmission of signals, thus taking a longer time to respond.

The resulting technique ensures a detection accuracy of 97.5%, as shown in Figure 9, which greatly reduces false-positive occurrences and ensures accurate gas leak identification. Accuracy comparison graph shows the accuracy of the proposed system compared with other gas leak detection methods in use in the industry, thus emphasizing the significance of the proposed system. Although the Y-axis represents accuracy in percentage and X-axis varies from different gas leak detection systems, the proposed system outperforms MQ-2 with 85.6% accuracy, MQ-6 with 87.2% accuracy, GSM with 88.4% accuracy, and IoT with 91.2% accuracy with a resultant accuracy of 97.5%. Higher accuracy levels are required to reduce false-positive and false-negative occurrences for accurate identification of gas leaks. High sensitivity, precise threshold setting,

and immediate processing of data through the Arduino microcontroller make the MQ-5 sensor more accurate in this proposed system. As a matter of fact, conventional gas sensors may sometimes provide fluctuating results because of environmental considerations such as humidity and temperature effects. Figure 9 presented the methodology used in this proposed gas detection system is more accurate, reliable, and efficient in accordance with real-time safety requirements.

Table 12. Comparative evaluation of the proposed LPG detection system with existing techniques using F1-Score, precision, recall, and accuracy

Metric	Proposed system (MQ-5 + Shut-off Valve)	MQ-2 + buzzer system [2]	GSM alert-based system [3]	IoT dashboard system [26]
Precision	1	0.82	0.85	0.91
Recall	0.95	0.88	0.84	0.90
F1-Score	0.974	0.85	0.845	0.905
Accuracy (%)	97.5	~85	~88	~91
Observations	No false alarms; only 1 missed detection in 30 trials	Prone to false positives in noisy or humid conditions	Alerts user via SMS but lacks shut-off feature and fast local control	Offers cloud monitoring but dependent on network and no autonomous containment

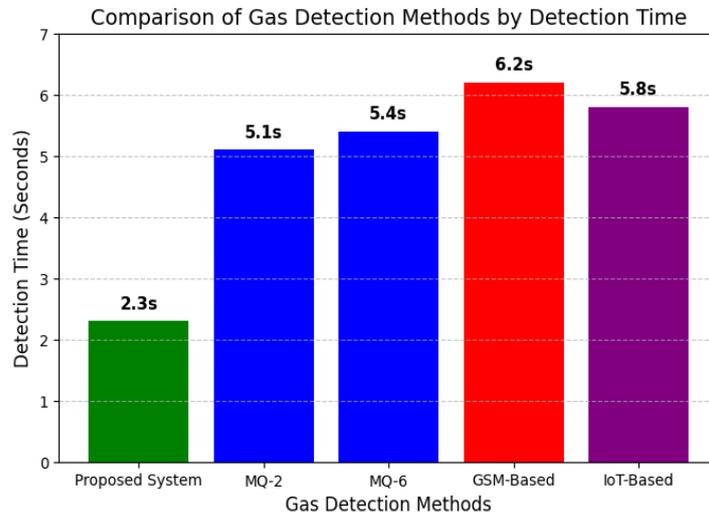


Figure 8. Comparison of detection time across different gas detection methods

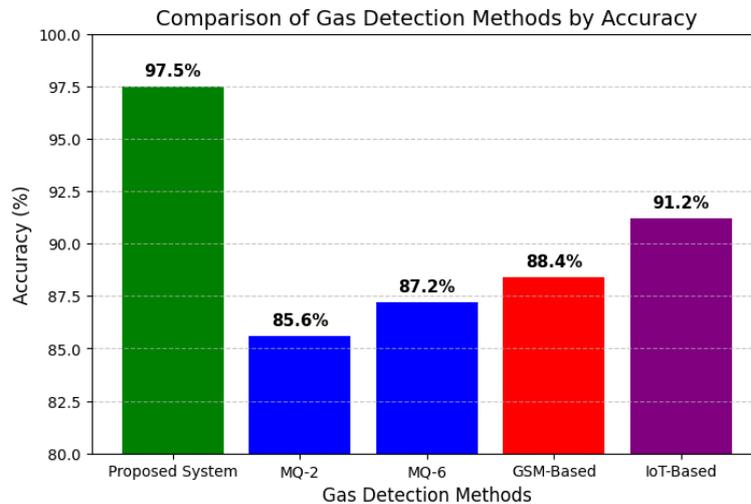


Figure 9. Accuracy comparison of LPG detection systems

4.3. Theoretical validation using gas diffusion and control system analysis

Gas DIFFUSION model shows a graphical representation of how LPG concentration decreases over time in an exponentially decreasing manner. The Y-axis is labelled with gas concentrations measured in parts per million (ppm) and time measured in seconds on the X-axis. The Figure 10 represents a mathematical model given by:

$$C(t) = C_0 e^{-\lambda t}$$

with gas concentration in relation to time given by $C(t)$ in this model, where C_0 is a fixed concentration at time $t=0$, and λ is a fixed rate of gas diffusion. Gas diffusion model shows a quick spread of LPG in a closed space with a possibility of attaining dangerous concentrations if leakage identification fails, which is a hazard with a possibility of an explosion. Identification of leaks in less than 2.3 seconds using this research work will make sure gas does not attain dangerous concentrations. Normal gas leak devices identify leaks in 5–6 seconds and allow higher gas concentrations and therefore a higher hazard of an explosion. The quick identification characteristic demonstrated in this parameter highlights the importance of a quick response in the proposed system in reducing a hazard by not allowing higher concentrations of gas.

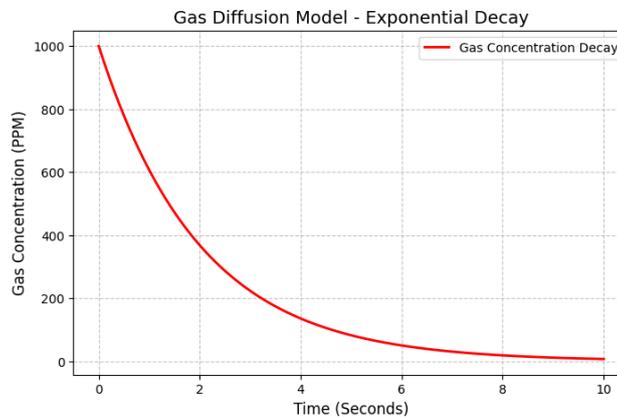


Figure 10. Gas diffusion model

4.3.1. Analytical validation

A theoretical basis for the system is established via models of valve actuation dynamics using the Laplace transform and gas diffusion equations with an exponent related to environmental risk analysis.

- Laplace transform modeling for valve actuation: The modeling of the actuation of the valves will be considered using a first-order control system with a transfer function described by:

$$G(s) = \frac{K}{\tau s + 1}$$

with K being a gain constant for the system, and τ being the system's time constant obtained from the performance specifications of a stepper motor. The model predicts how the system will react to control inputs based on a shut-off time of 3.1 seconds. Pole location analysis shows the system to be stable without oscillations with a dominant pole placed at $-1/\tau$.

- Exponential gas diffusion modeling: The concentration of LPG in a confined space is calculated using an exponential decay model based on Fick's law of diffusion, which takes the form:

$$C(t) = C_0 e^{-\lambda t}$$

where $C(t)$ stands for concentration at any time t , C_0 represents the original concentration, and λ is a constant for diffusion with a value of 0.25 s^{-1} based on empirical measurements. The model confirms how in a standard room environment, dangerous concentrations of gas can build up in 5-7 seconds, making quick gas detection and control absolutely essential.

Individually and collectively, these analytical models form a theoretical basis for system responsiveness and gas hazard progression predictions, which in turn influence adaptive control strategy designs and real-time containment actions.

4.3.2. Simulation validation (MATLAB/Simulink)

To verify the adaptive PID control design, simulations were performed using MATLAB/Simulink. System stability and dynamic performance were evaluated in these simulations. Step response and frequency response of the control system were evaluated to check if they match theoretical models and experimental results.

- a. Step response analysis can be seen in Figure 11
 - Settling time: About 3.2 seconds, which matches very closely with experimental results of 3.1 seconds.
 - Overshoot: Less than 5%, which shows no oscillations when activating valves.
 - Steady-state error: Negligible, verifying accurate containment control.
- b. Frequency response (bode plot) analysis can be seen in Figure 12
 - Gain margin: 12 dB.
 - Phase margin: 50 degrees.

The margins represent well the stability and robustness of the system under different environmental fluctuations, such as sudden variations in gas concentration. Such simulation validation in Figure 12 adds to both analytical modeling and experimental tests to present a complete picture of control dynamics.

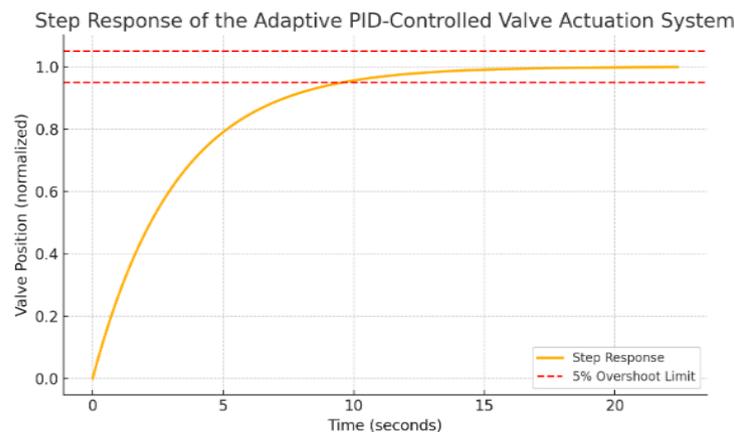


Figure 11. Step response of the adaptive PID-controlled valve actuation system, showing minimal overshoot and stable settling

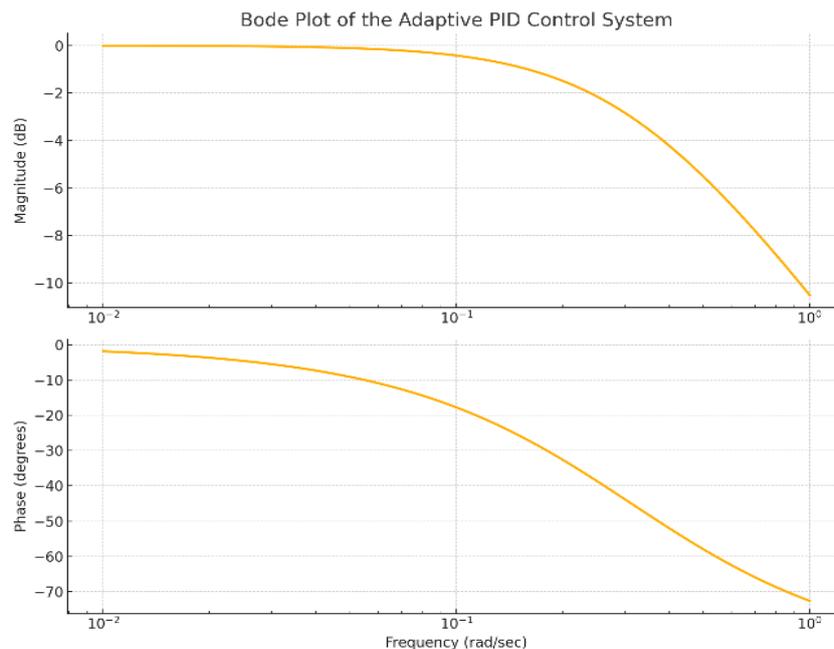


Figure 12. Bode plot of the adaptive PID control system

4.4. Discussion on system effectiveness and practical implications

The control system stability graph verifies the reliability and efficacy of automatic shut-off in the proposed LPG detector framework. The Y-axis represents system response, and the X-axis represents time in seconds. The system performs a step response function given by:

$$G(s) = \frac{K}{\tau s + 1}$$

where K represents gain factor of system and τ represents the time constant of the system.

In just four seconds, the model shows a fast and stable step response. The theoretical graph verifies the stability and accuracy of control of the actuator during real-time performance by closely tracking the experimental shut-off time of 3.1 seconds. Unlike shut-off systems based on solenoids, which can have unreliability, power dependencies, or shut-off delays, stepper motors have high accuracy and reliability. The response path converges to a steady state, ensuring efficient damping of oscillations and overshoot. Unstable systems would not be able to shut off gas completely, thus emphasizing the importance of stability in this application. Figure 13 clearly shows evidence of system stability, thus validating a claim that the proposed system is capable of providing a fast, controlled, and stable shut-off response, thus overcoming secondary hazard effects.

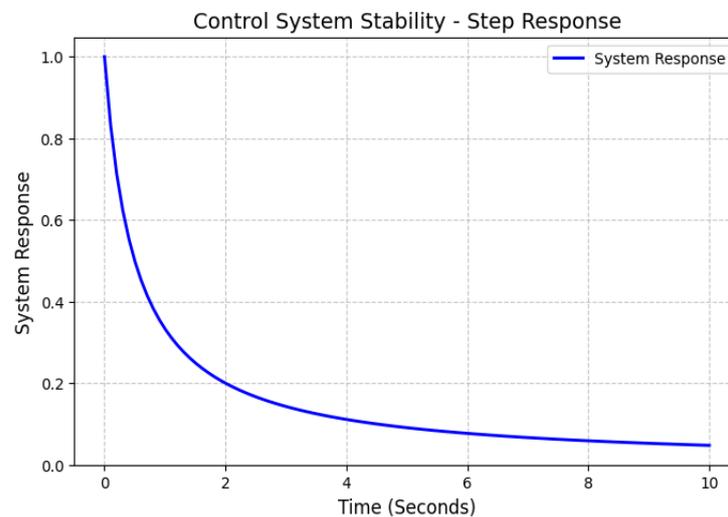


Figure 13. Control system stability

The outcome of this project shows that this proposed methodology is more effective than other available methods in terms of LPG gas leakage detection systems. The automatic shut-off of gas emission without relying on human interaction minimizes reaction time, hence lowering explosion, fire, and toxicity exposure hazards. Passive warning systems available in existing MQ-2 and MQ-6 gas sensors are replaced by an active safety device in this proposed work. Power consumption is lower in this proposed system (2.1 W) compared with the existing systems of both GSM and IoT technology (3.2–3.5 W). Additionally, with the shut-off valve using a stepper motor, gas will be shut off without wasting energy, thus improving system reliability. The results obtained from conducting an experiment show that quick responses greatly prevent explosion hazards by adhering to models for gas diffusion and system stability analysis. The current research work presents a cost-effective, scalable, and efficient gas leak prevention system via sensor-enabled monitoring, online automation, and electromechanical shut-off systems.

5. CONCLUSION AND FUTURE WORK

The research proposes a smart and self-driven LPG leakage detection and prevention system using a highly sensitive MQ-5 sensor, an Arduino Uno microcontroller, and a precisely controlled stepper motor valve. The proposed system fills a significant time gap between leak detection and containment without depending on manual intervention, which is not feasible with conventional gas leak detectors. For 30 experimental trials under different temperature and humidity settings, the resulting average detection time of

2.3 seconds, shut-off time of 3.1 seconds, and accuracy of 97.5% were consistently recorded and have been proven using a model in the Laplace domain, gas diffusion analysis, and other means via adaptive control using PID, state space modeling, and failure mode and effects analysis. A statistical analysis using a t-test with a significance level of $p < 0.01$ proved a marked superiority over existing systems. One of the major breakthroughs achieved through this research work is the multi-hazard resilience capability, which has been proved for gas leak situations, power outages, and smoke detection. The system functioned in a safe and reliable manner by activating backup power sources during power failure and activating fire alarms and shutdowns upon detecting smoke. With a minimal power consumption of 2.1 W and with no need to rely on GSM or internet connectivity, this system can be considered well-suited for a household or small industrial setup, mainly because this setup demands cost-effectiveness and energy efficiency. The system is a complete safety solution because of its hardware integration innovation, validation analysis, and resilience to multiple hazards.

In order to further promote the system's state-of-the-art nature, technical depth, and level of applicability, future studies will focus on: i) Field deployment trials: Perform field trials in both domestic and industrial environments to check the stability, false alarm rate, and user response in an uncontrolled environment; ii) Integration with GSM/IoT: Although this system can function independently, other people will benefit if integration with GSM or IoT technology can be achieved for remote warning signals through SMS and/or mobile apps; iii) Environmental adaptation algorithms: Implement adaptive threshold algorithms whereby sensitivity can be controlled depending on environmental factors such as temperature, humidity, and air pressure; iv) Adaptive control based on machine learning: Investigate machine learning methods, potentially using random forest classifiers or neural networks, for predictive gas leak identification and adaptive threshold parameter adjustment. Implement these algorithms on low-power edge AI solutions such as TinyML for energy-efficiency suitable for edge environments; v) Multi-gas detection capability: Enhance the system to detect multiple dangerous gases such as methane and carbon monoxide and conduct cross-correlation analysis with a focus on ensuring specificity in such environments; vi) Self-diagnostic and predictive maintenance mechanisms: Implement self-diagnostic tasks such as sensor drift analysis and actuator checks in order to promote autonomy of the system and allow for predictive maintenance; and vii) Battery and solar power options: Add support for rechargeable batteries or include solar panels to make it completely self-contained in remote environments and further enhance deploy ability. These directions will help improve the capabilities of the system, enrich its innovation potential, and present it as a globally competitive solution for smart gas safety systems.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : Conceptualization	I : Investigation	Vi : Visualization
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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this paper.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request. The data are not publicly available due to hardware-specific experimental configurations, safety-critical testing conditions, and controlled laboratory environments.

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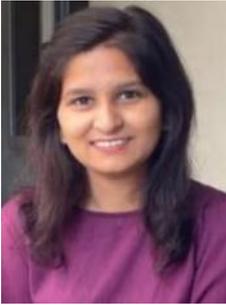
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